MODELLING SOLID PROPULSION STAGES

(Contract n° 4000105079/11/NL/KML)

EXECUTIVE SUMMARY REPORT

Prepared by *Preparato da*	A. Pasini	Date: *Data:*	27/11/2012
Agreed by *Controllato da*	L. Torre	Date: *Data:*	27/11/2012
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AUTHOR (S) *Autore/i*	ORGANIZATION (S) *Organizzazione/i*	ADDRESS *Indirizzo*	
A. Pasini	Alta S.p.A.	Alta S.p.A. Via Gherardesca, 5 56121, Ospedaletto-Pisa, Italy Phone: +39 050 967211 - Fax: +39 050 974094	
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ABSTRACT
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This document represents the Executive Summary Report of the project "Modelling Solid Propulsion Stages", contract n° 4000105079/11/NL/KML.

KEY WORDS
Parole chiave
Solid Rocket Motor, Propulsion, Solid Grain, ESA CDF, SPUD, Excel Workbook.

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1 Introduction

This document represents the Executive Summary Report of the activity *"Modelling Solid Propulsion Stages"*, carried out by ALTA S.p.A. under the ESA/ESTEC contract n. 4000105079/11/NL/KML.
More specifically, this document concisely summarises the main findings of the contract with a language suitable for non-experts in the field of solid propulsion rockets and appropriate for publication.

2 SPUD: a User Friendly Solid Rocket Motor Design Tool

Historically, Solid Rocket Motors (SRMs) have been introduced during the Second World War for bullets, cartridges and ammunitions. In the late fifties (1957), from military applications this technology was borrowed by space launcher industries of the main actors of the space race. Polaris was the first application of SRMs for ballistic missiles and the Mercury mission was the first space mission carrying SRMs retrorockets. Over the last fifty years, solid propulsion has been successfully employed for a number of small launchers, and first stages, boosters, strap on of heavy launchers. During seventies the segmented solid boosters of Space Shuttle and the apogee boost SRMs for geostationary satellite have been developed and operated.

Figure 2.1 Some SRMs for heavy space launchers and some small launchers completely SRMs equipped.

The keys of solid propulsion success are its capability to allow for low risk, high performance, low cost, high storability and fast operation. These aspects made solid propulsion one of the first steps for countries worldwide for the development of Earth-to-space capabilities.
The huge success of this technology, however, has been also applied for space operations. Also orbit adjustments, reorientation and separation maneuvers, retromotors (i.e. Mars Exploration Rover), first

kicks for orbital changing maneuvers (e.g. apogee/perigee burns) and spin/de-spin motors have been implemented via SRMs.

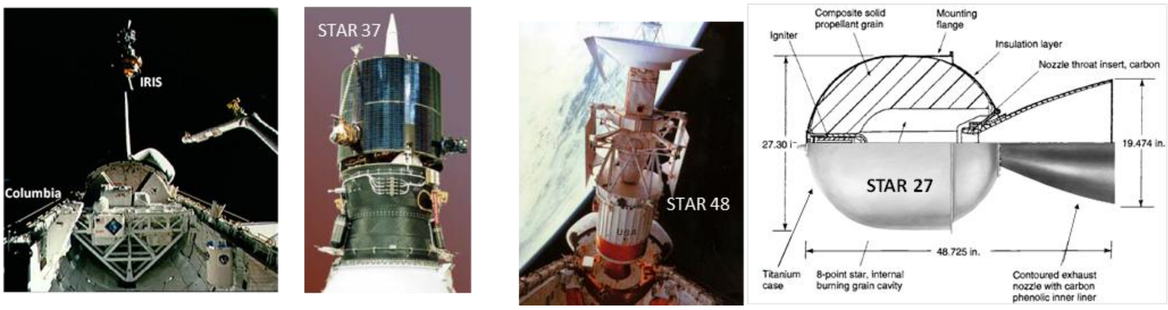

Figure 2.2 Typical in-space applications of SRMs.

In the next future, the use of solid rocket motors for space applications is not expected to remain confined to the sectors of launchers and Lunar or interplanetary missions, but will most likely be extended to other fields more closely related to satellite propulsion. One of these fields is represented by the de-orbiting of unused platforms at the end of their life, for which solid propulsion is one of the two options (together with electric propulsion) recently identified by the ESA Concurrent Design Facility.

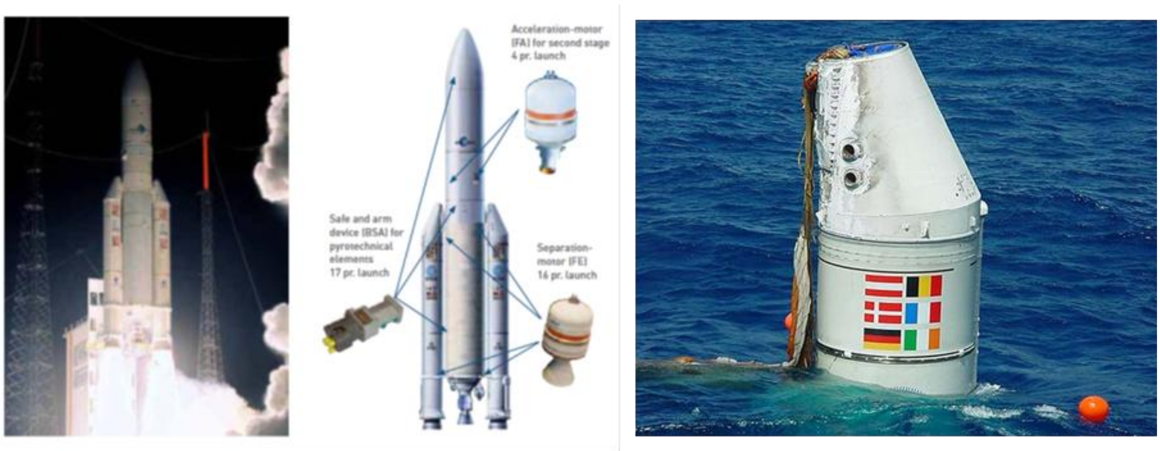

Figure 2.3 Ariane 5 with a schematics of the position of the Separation and Acceleration Motors together with the position of the safe and arm devices.

Also nowadays, solid propulsion still represents a keystone for a number of missions and launchers. USA, Europe, China and Japan have planned several missions relying on this technology and a number of future small launchers or parts of heavy lifter are designed pushing the innovation of this technology.

The development of solid motors brought also a number of technical advancements like the development of high strength composite cases, low density insulation, continuous mixing for material processing and, in general, advanced detailed simulations. These enabling technologies, together with efficient production processes have been identified as crucial to reduce cost and improve reliability. The key aspects improved over years of SRMs development are the controlled mixing/casting, the robust grain characteristics prediction and the minimal insulation requirements. Moreover, the general trend shows the replacement of metallic case with lighter composites in modern solid rocket motors.

The solid rocket motor technology proved to be flexible and versatile over years and a broad range of achievable thrust level and specific impulse can be obtained by the various SRMs.
Additionally, it has to be noted that nowadays there exists a robust industrial organization in Europe (Snecma, EADS, SNPE) making the state of the art of this technology independent from USA.
In general, solid propulsion motors can only deliver their total impulse in one firing, because off-modulation is not possible; this is the main drawback of this technology limiting its applications (although hybrid motors have been developed to overcome this issue).
Due to this aspect, among chemical rockets, the highest level of integration between mission requirements and design features is required for solid propellant motors. Thus, even at the early stage of mission analysis there is the need of effective tools for preliminary design and performance prediction of solid propellant rockets.
The activity *"Modelling Solid Propulsion Stages"*, carried out by ALTA S.p.A., aimed at evaluating the state-of-the-art of European and US solid propulsion stages and at creating an Excel-based design model/workbook for solid propulsion stages. The developed tool called SPUD was intended to be used, amongst others, by the ESA Concurrent Design Facility for either selecting existing solid rocket motors from a suitably populated database or creating preliminary designs for new solid rocket motors. Having a workbook to model stages based on solid propulsion will help assessment studies to perform trade-offs taking solid propulsion stages into account.

Figure 2.4 Logo of the SPUD program.

SPUD (Solid Propulsion Unit Design) is an easy-to-use multi-platform tool for the preliminary design and the performance prediction of propulsion stages powered by solid propellant rocket motors. It features an intuitive graphical user interface with convenient grouping the input parameters and analysis results.
By providing a few mission inputs such as vehicle initial mass, mission velocity gain, and required payload mass, the program identifies the design parameters according to the envelope, ambient and propulsive constraints and the designer choices, determines the mass budget of the overall solid propulsion stage, and predicts the theoretical rocket performance of the solid stage. Moreover, the program allows the user to identify existing rocket motors that can accomplish the mission requirements. The results of calculation can also be used within more complex mission analysis studies. The calculation method is based on several reduced order models for the treatment of ballistic analysis, grain geometry calculations, mass budget estimation, spin stabilized AOCS design etc.

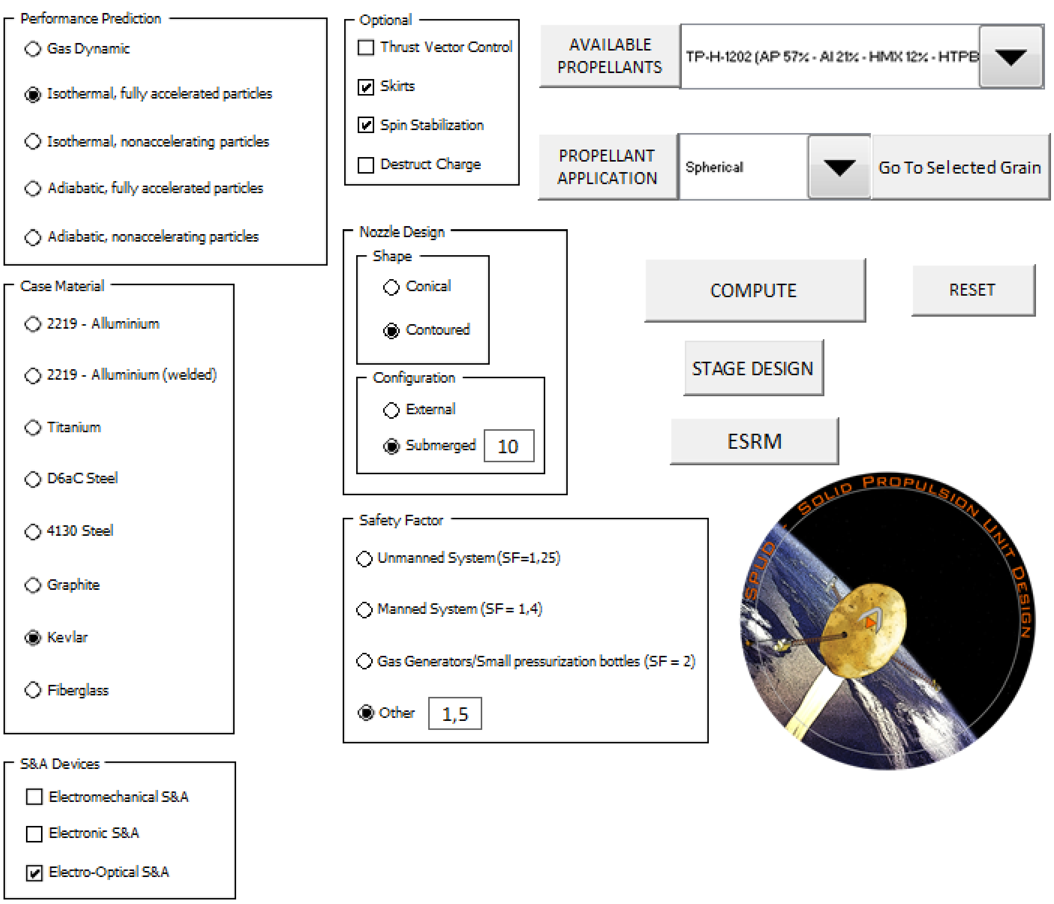

Figure 2.5 Layout of the Graphical User Interface for settings the design options.

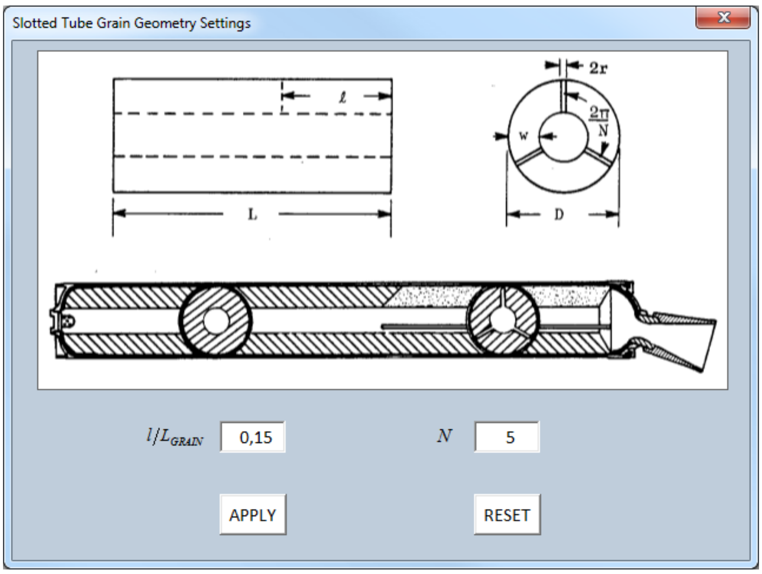

Figure 2.6 Typical dialogue box for advanced settings of the grain configurations.

The key aspects of the SPUD program are the user friendliness and the sound of the models at the base of the Excel workbook.
SPUD is an Excel workbook that features macros suitably developed in VBA programming language. The intuitive graphical user interface and the several dialogue boxes in VBA for basic and advanced settings guarantee the user friendliness. Moreover, according to the knowledge and experience of the user, the program allows both for a rapid preliminary design based on its basic functions or a more refined one obtained by means of its advanced functions.
The design sequence for a new design motor starts from the mission analysis requirements and it includes the selection of the suitable propellant within an easy updatable propellants database, the identification of the independent/dependent design parameters, the selection of the grain configuration and the preliminary assessment of the ballistic and propulsive performance.

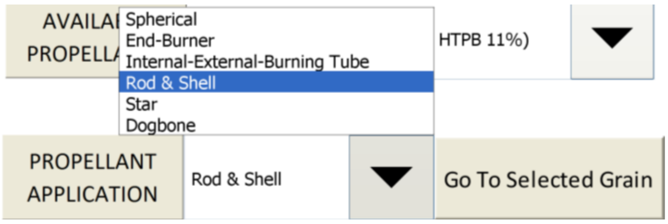

Figure 2.7 Typical list of available grain configurations for a specific mission.

The assessment of the propulsive performance is based on an accurate ballistics analysis and an integrated treatment of the acceleration process inside the nozzle.

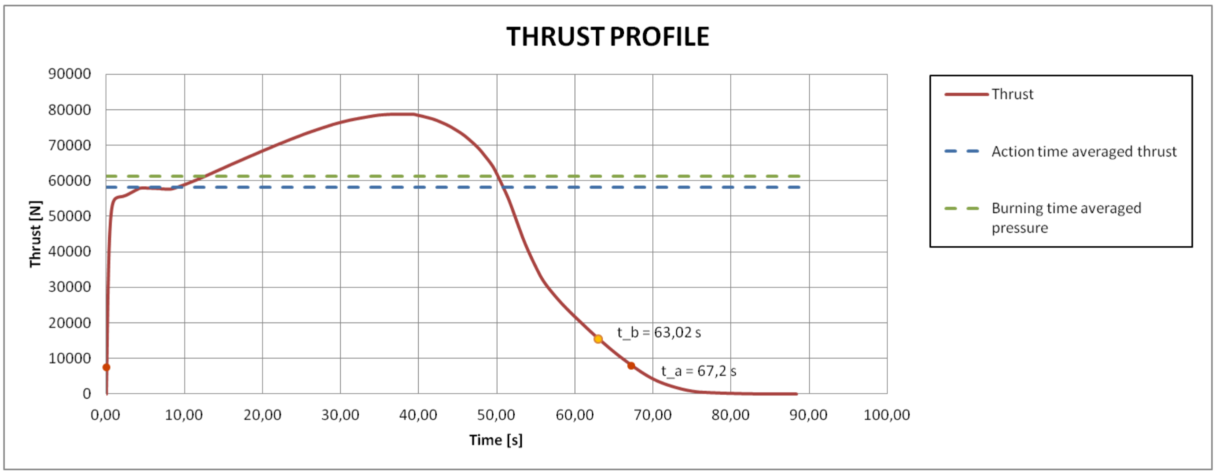

Figure 2.8 Typical computed thrust profile.

The ballistics analysis is performed with a lumped-parameter method (zero-dimensional analysis). The time-evolution of chamber pressure, available chamber volume, throat diameter and web is obtained as a result of the integration of a system of four differential equations performed with the 4^{th} order Runge-Kutta method. For each of the twelve available grain configurations (such as finocyl, star, dogbone, wagon wheel, spherical etc.), the burning area, the port perimeter and the port area are computed as a function of the local web, defined as the linear amount of propellant consumed as measured normal to the local surface, in order to obtain a more realistic time evolution of the chamber pressure capable of taking into account also the effects of the erosive burning and the eventual presence of throat erosion.

The effectiveness of the acceleration process inside the nozzle is assessed by means of a quasi-1D compressible inviscid steady flow approximation for single-phase gaseous flow and a quasi 1D dusty adiabatic inviscid steady flow approximation for two-phase flow both corrected by suitable efficiencies for kinetic, boundary layers and nozzle submergence and divergence losses.

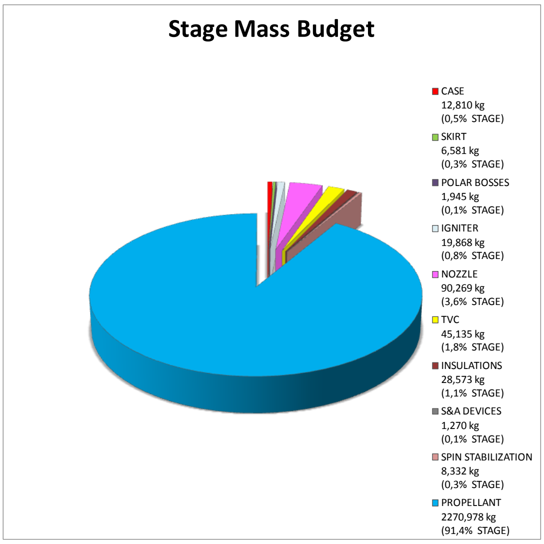

Figure 2.9 Typical pie-chart of the stage mass budget.

On other hand, the preliminary components sizing for mass estimations employs semi-empirical/analytical formulas for mass estimation of propellant, motor case, thrust skirts, polar bosses, igniter, nozzle, insulations, thrust vector control, AOCS for spin stabilization, safety & arm devices.
In particular, the design of the AOCS for spin stabilization relies on simplified models for computing the AOCS requirements (such as disturbance torque and required spin velocity) and estimating the centroidal distance and inertial properties of the spacecraft.

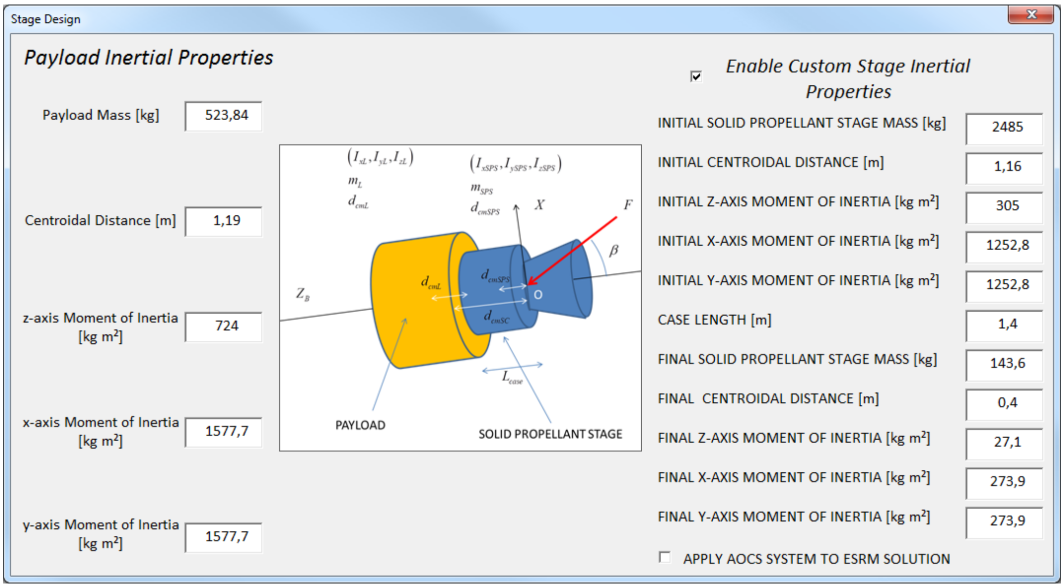

Figure 2.10 Dialogue box for designing the AOCS for spin stabilization.

Another important feature of the program is the capability of identifying and ranking existing solid rocket motors suitable for accomplishing specific mission requirements within a well-populated and easy-updatable database of solid propulsion motors. Three different criteria are exploited by the SPUD program to assess the best solution according to different starting assumptions such as fixed spacecraft initial mass or fixed payload mass or simultaneous minimization of the initial mass of the vehicle and maximization of the payload mass of the spacecraft. Moreover, the SPUD program is able to quantify the amount of the propellant that should be eventually unloaded to satisfy the mission requirements.

EXISTING SOLID ROCKET MOTOR PERFORMANCES	
Name	**Star 24**
Propellant	*TP-H-3062*
Δv	1233,2 m/s (100,0 % of the desired velocity gain)
m_L	297,1 kg (97,4 % of the desired payload)
m_E	18,3 kg
m_P	176,5 kg (23,4 kg of propellant unloaded)
m_0	491,9 kg
a_{max}	62,33 m/s² (6,35 g)
F_{mean}	19661,14 N
t_b	24,91 s (85,9 % of the desired burning time)
L_{stage}	1028,70 mm (49,6 % of the maximum stage length)
D_{stage}	622,30 mm (58,7 % of the maximum stage diameter)
$p_{c,max}$	3,61 MPa
f_{prop}	0,906
I	489763,83 N·s
$I_{sp,eff}$	282,90 s

Table 2.1 Typical computed performance of an existing solid rocket motor.

The preliminary validation of the Excel workbook has been successfully carried out according to three mission profiles towards L2 (the second Lagragian point of the Sun-Earth system), Mars and Jupiter. The wet mass of the spacecraft and the initial parking orbit have been based on three different launcher scenarios such as VEGA LEO, SOYUZ LEO and SOYUZ-Fregat GTO. Except for the case towards L2 that needs only one solid propulsion stage for the insertion into the parabolic transfer orbit, the spacecraft is supposed to comprise the satellite (i.e the payload), an insertion stage and a braking stage both powered with solid propellant. All the three different launcher scenarios allow for the missions to L2 and Mars while only the Soyuz cases permit to reach Jupiter. For all these cases, the SPUD program has been able to provide two solutions based, respectively, on a new design and on existing hardware.

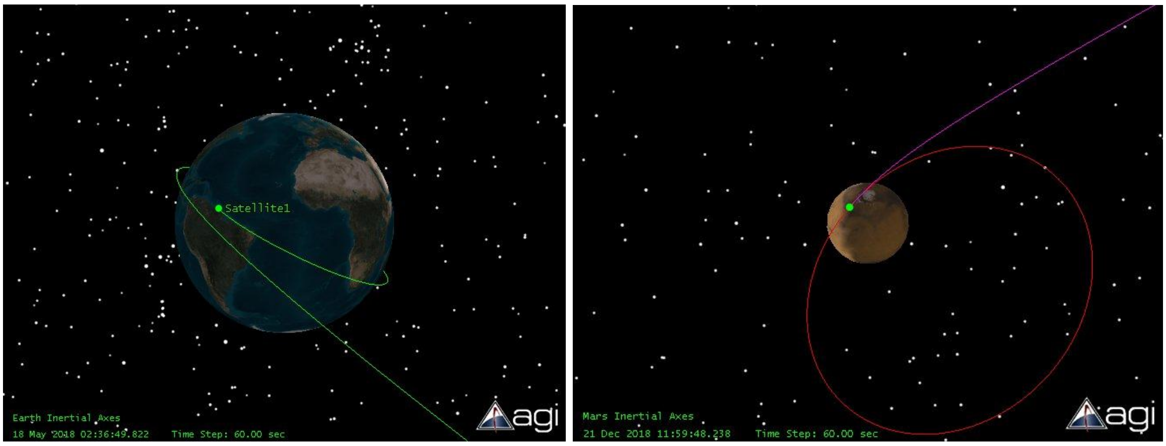

Figure 2.11 Interplanetary mission from Earth to Mars based on VEGA LEO.

It is worth noticing that the most interesting solution obtained by the SPUD program for these missions is the possibility of inserting over 290 kg of payload in orbit around Mars (SSTL-300 platform type) based on the VEGA LEO launcher scenario.
The SPUD program proved to be a versatile tool for the preliminary design of a solid propulsion stage.